SoF Laser Diode

18/11/2024

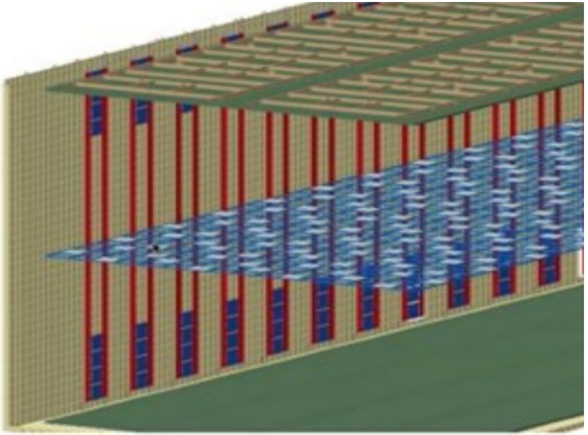
Outline

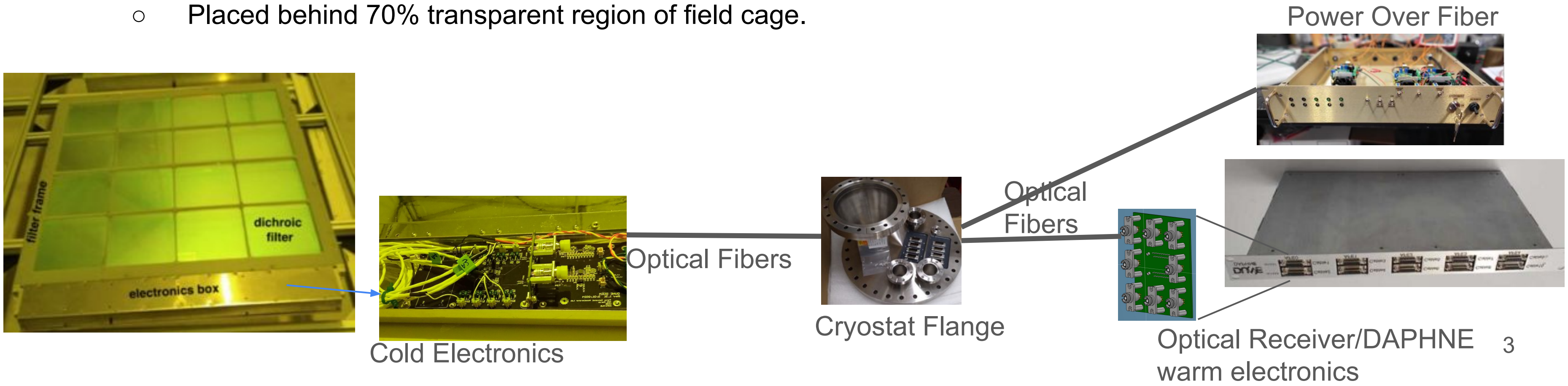
stage-1 PRR for the laser diodes, it is needed due to financing plan (in2p3 groups). The Signal-over-Fiber transmitter card (holds 2 lasers) will be part of a future stage-2 PRR.

- General Introduction to FD2 Photon Detector and Signal Over Fiber
- SOF Specifications
- SOF laser diode specifications
- Results
    - SOF Performance (dynamic range, Signal-to-Noise from coldbox, CERN test-stand)
    - Laser response (current vs optical power) from dedicated tests at Fermilab
- Laser longevity test performed at Fermilab
- Procurement/Shipping/Storage
- Schedule
- QC Plan
- Answer summary

Introduction

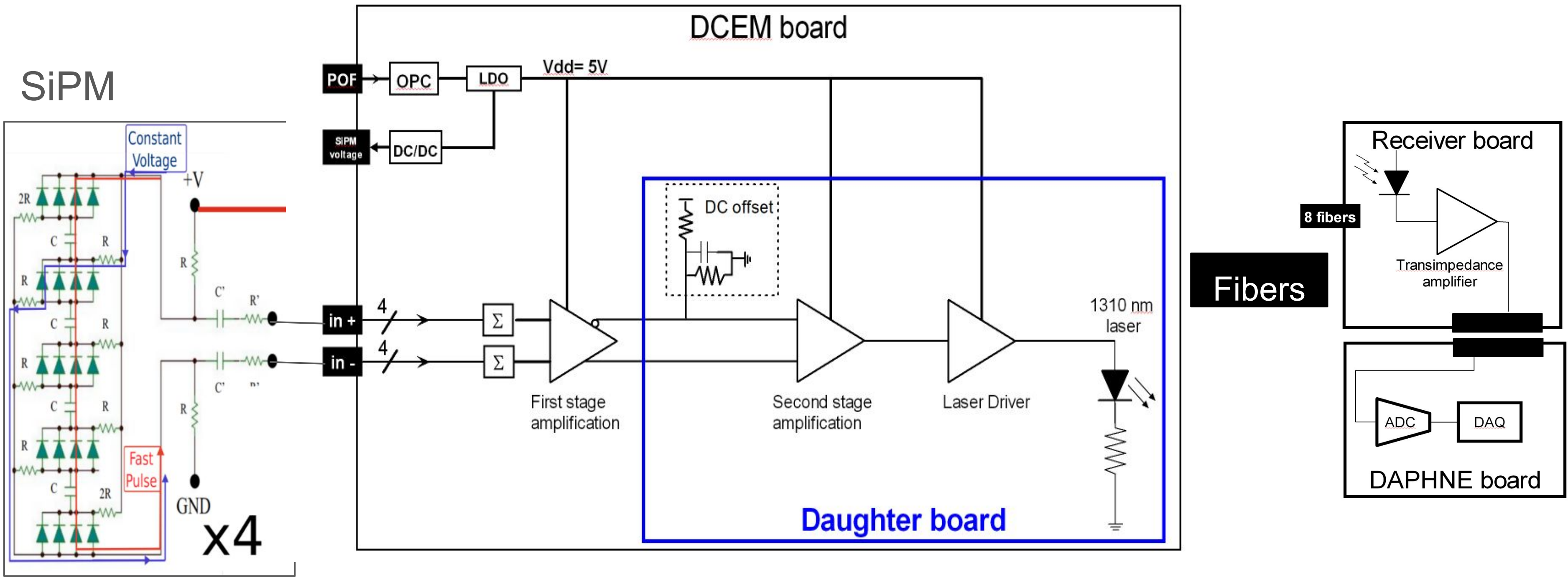
- Photon Detector System collects scintillation light from neutrino interactions in the LAr detector volume
  - Provides event timing and supplemental energy measurement
- 320 PD modules mounted in cathode plane
  - High voltage (-300kV) of cathode requires powering and reading out with optical fiber.
  - Two-sided module for detecting light from below and above.
- 320 (long side wall) + 32 (cryostat end wall) mounted outside field cage near cryostat membrane
  - Single-sided module.
  - Powered and read out with copper cables.
  - Placed behind 70% transparent region of field cage.





SOF Electronics

- Read-out electronics for Cathode-mounted Arapucas
- Arapuca - 160 SiPMS total read-out over 2 channels (4 x 20 SiPMs into each channel)



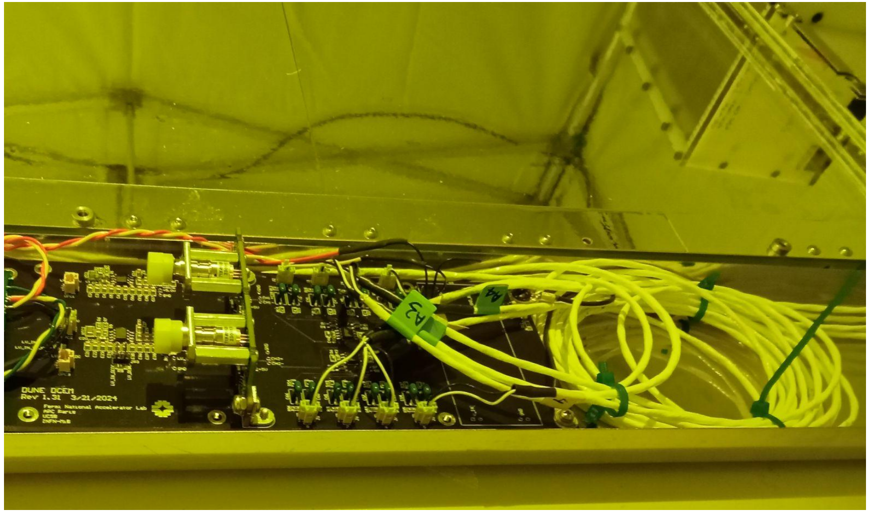
SOF specifications

- DCEM v1.31 motherboard
- SOF daughterboard 1.1
  - SiGe version with transistor
  - [CMOS version]
- Laser
  - DUNE Custom LaserMate
- Fibers 62.5um MM black-jacketed fiber (40m) MH GoPower (**FPC-062CDFC-04015BB)**
- Optical receiver and digitizer
  - 8-channel optical receiver (prototype 2-channel), DAPHNE v3 - VD
  - Single channel commercial receiver (koheron), CAEN 14-bit digitizer

Objective: S/N (single photoelectron) > 4

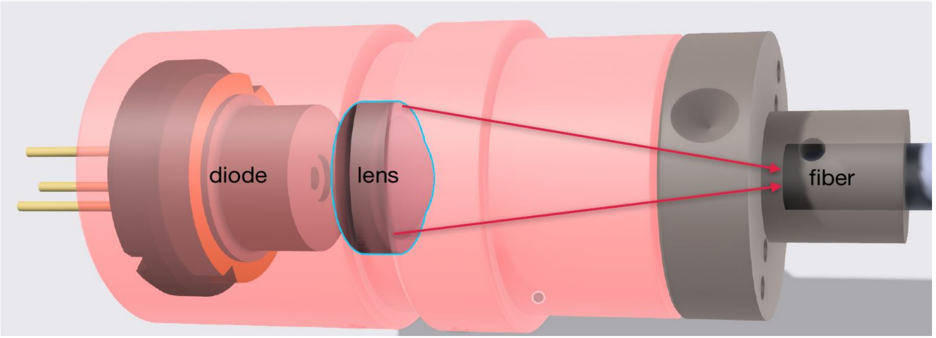
Dynamic range > 1500 pes (per channel)

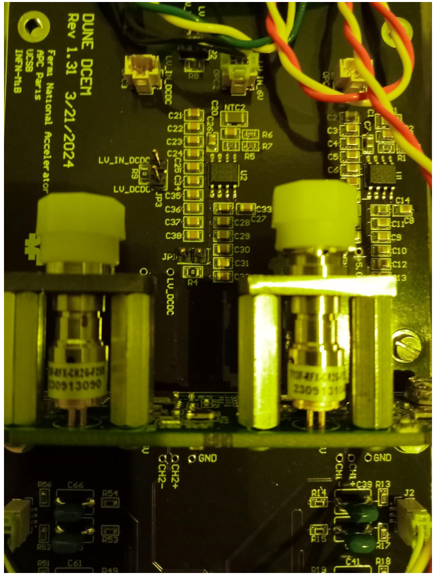
Longevity aim to lose < 1% of Arapuca (NB, 2 channels per Arapuca) over 30 years



SOF laser diode specification

- LaserMate: T13F-RFX-CR2G-F25
- Fabry-Perot laser diodes 1310nm for data communications
- Laser Class 1 product
- Max optical power 2mW
- Customised for use in Liquid argon
  - Lengthed focal point by 2.5mm (defocused)
  - Perforated housing
  - Cryogenic glue used EPO-TEK 301-2 – transmission> 98% @ 1200-1600 nm
- More details in PUMA (Request For Quotation)
- Signal/Electronics require:
  - frequency response greater than our signal (>20 MHz)
  - threshold current in LAr < 3 mA
  - optical output (0 - 1.5 mW optical power for currents from 2 - 30 mA)





SOF Specifications

Characteristics of the system parts. Items in bold indicate the component limits the over-all system (for example DCEM op-amp limits the overall bandwidth). *Dispersion on optical coupling (laser->fiber) leads to variation in the number of PEs at saturation (signal max).

	SiPM	DCEM	Laser driver	Laser	Receiver	DAPHNE
Bandwidth (MHz)	Signal ~10MHz	**20MHz**	>20 MHz	>100 MHz	100 MHz	~20 - 30MHz
Baseline	–	–	~3mA	~30uW	~90mV	—-
Single Photoelectron (amplitude)	+/- 15uV	+/- 0.3mV	7.5uA	~0.3-0.5uW	0.5-1.5mV	10-20 ADC (variable gain)
Signal Max. 1500-2000 PEs	+/- 22 - 30 mV	+/- 450 – 600 mV	11-15mA	~0.7mW*	**1.7V** [4kΩ]	**1.7V [vgain dependent]**

Laser does not limit system [max power ~2mW]

Large batch tests of SOF Laser Diodes

Gained more experience in knowledge on these devices and performance.

110 laser diodes purchased (Fermilab), 30 (APC).

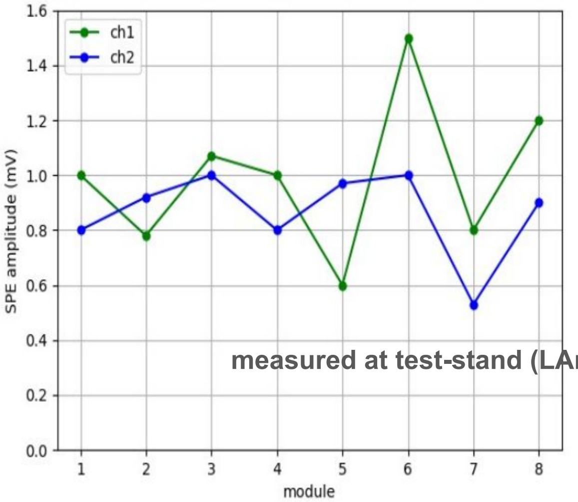
Will show results from:

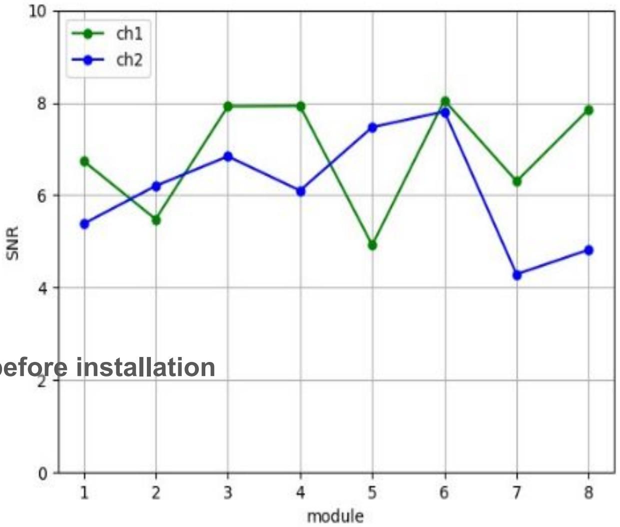
- 48 from longevity study (TallBo)
- 35 characterized in LAr (Fermilab)
- 8 (Jan), 4 (March), 8 (November) installed in coldbox tests
- 16 installed in protoDUNE-VD

ProtoDUNE-VD installation

8 cathode and 8 membrane modules - updates on electronic box, dichroic filters, wavelength-shifter, power-over-fiber and **Signal-over-Fiber:**

- **Lasers tested and selected (Fermilab)**
- **new PCBs (final)**
- **4 modules with SiGe op-amps (new) - modules 1-4 (CMOS modules 5-8)**

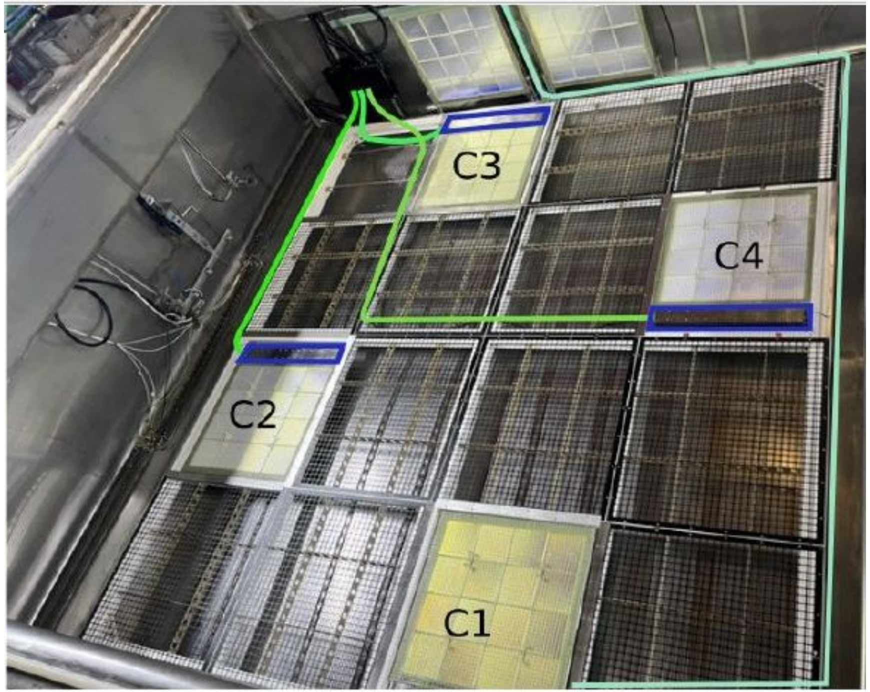




measured at test-stand (LAr) before installation

Cold Box runs

- Jan 2024
  - Reduced light level out of SOF
  - Installed 2-channel prototype receiver coupled to DAPHNE
- April 2024
  - First coldbox test of new SiGe SOF
  - Data taken with koheron/CAEN digitiser and prototype receiver/DAPHNE
- Nov 2024
  - Optimise performance with receiver gain settings



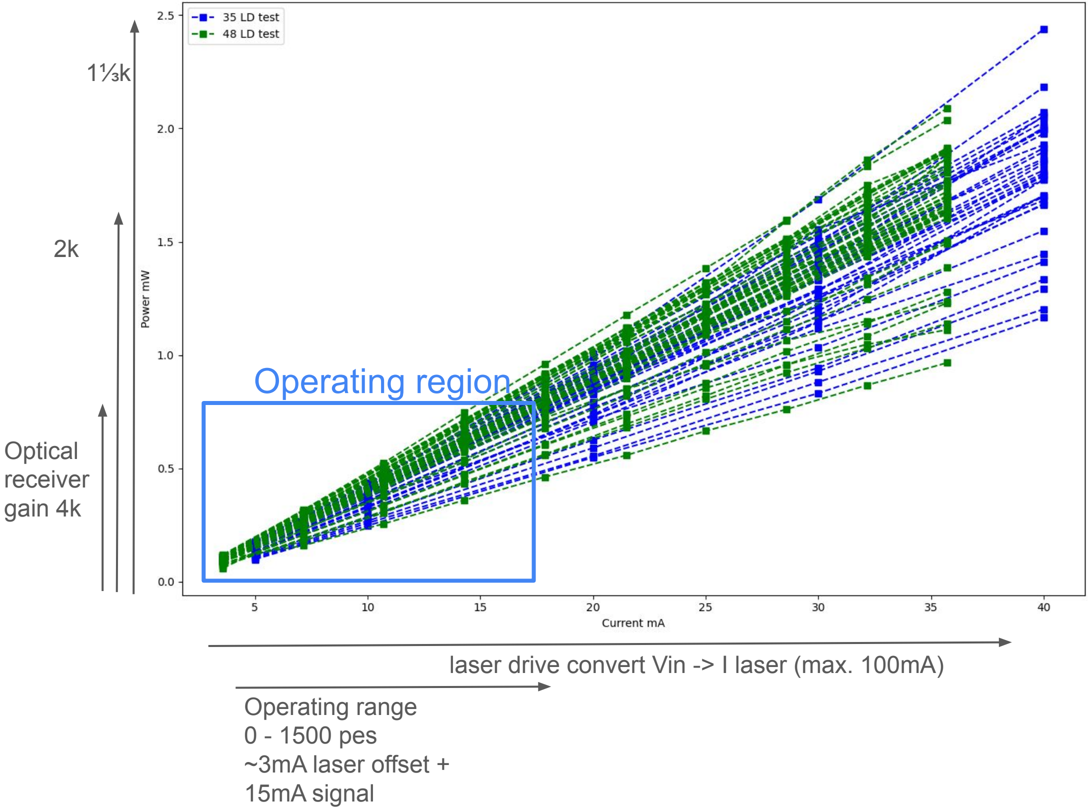
Cold Box Results April 2024 - Signal-to-Noise

- First, encouraging results from DAPHNE V2 (modified to connect 2 channel)
- SNR all greater than 4

C1/C2 – CMOS C3/C4 – SiGe		Koheron +CAEN		2-channel receiver + DAPHNE V2 (Vgain=0.3V)	
		SPE (ADC)	SNR	SPE (ADC)	SNR
C1	ch1	7	8.8	22	6.5
	ch2	6.3	7.9	14	4.5
C2	ch1	6.3	6	20	7
	ch2	5.1	6.2	16	4.4
C3	ch1	6.1	10.1	20	7-8
	ch2	5.4	6.1	21	5.4
C4	ch1	4.1	5.9	19	4.8
	ch2	6.4	5.3	35	6.8

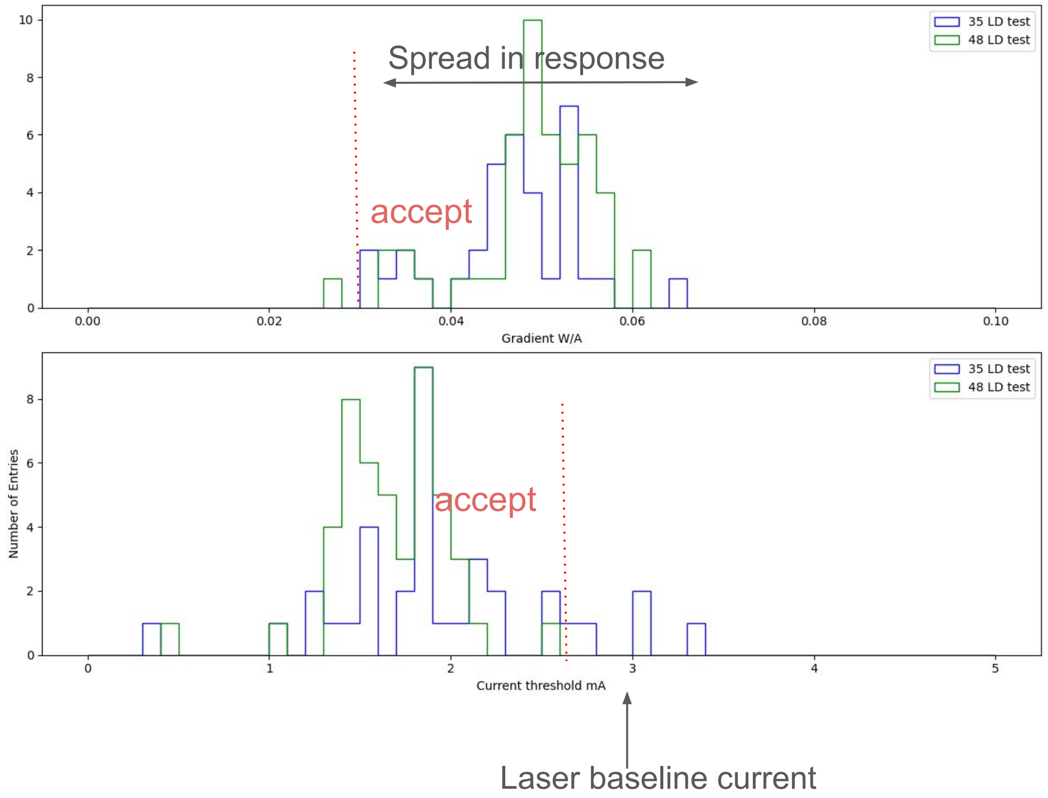
Specifications for SOF system - Dynamic

- Dynamic range (measured in coldbox) 1500-2000 pes
- Operating range in blue box
  - Laser current 3 – 18mA
  - Optical power – ~0.7 mW
- Optical receiver saturation (4k gain) ~0.7 mW
  - Gain (resistor dependent) 1.3kΩ - 4kΩ



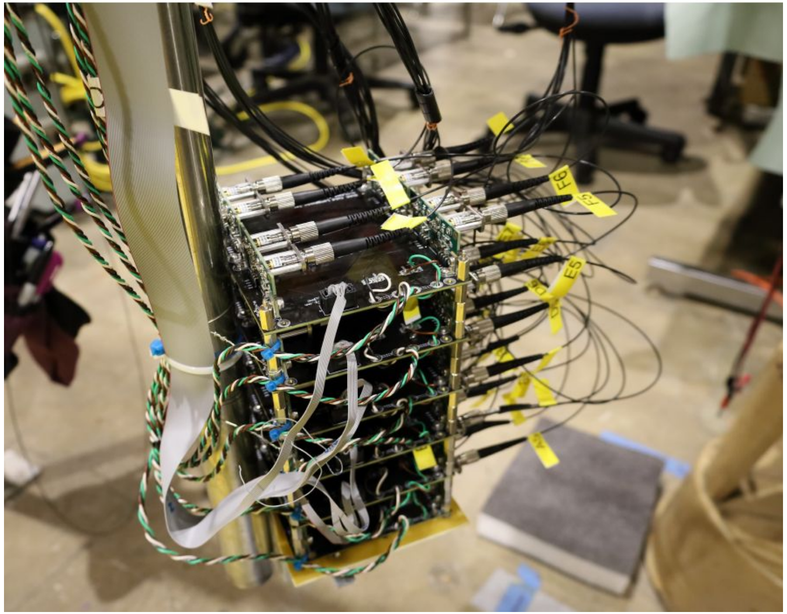
Specifications for SOF system -

- Linear fits to laser response
  - Gradient (mW/mA)
  - Current threshold
- Baseline current
  - Cold box ~2.6mA
  - Can increase >3 mA
- Added preliminary acceptance lines (red dashed)
  - Would reject 6 / 83 (~7%)
- Spread in gradient factor ~2
- Adjust DAPHNE gain (receiver)
  - DAPHNE gain adjustable in software
  - Receiver - resistor modification
- 10% spares planned (purchase 710 lasers)
- Can buy more lasers if needed (lead time 10 weeks)



Noble Liquid Test Facility (NLTF) - PAB, Fermilab

- TallBo - 450 l cryostat (up to 2m LAr depth)
  - Equivalent pressure (6-8m deep)
- Operated 24 March – 20 August 2024
- 5 months of continuous operation of 48 lasers
- Fixed current and pulse testing
- Laser response measured before and after



Remote controls ONLY. The rack is physically locked with a key to prevent unauthorized access

Optical power meters

Power supply, temperature monitor, pulse generator

PC for controls and DAQ

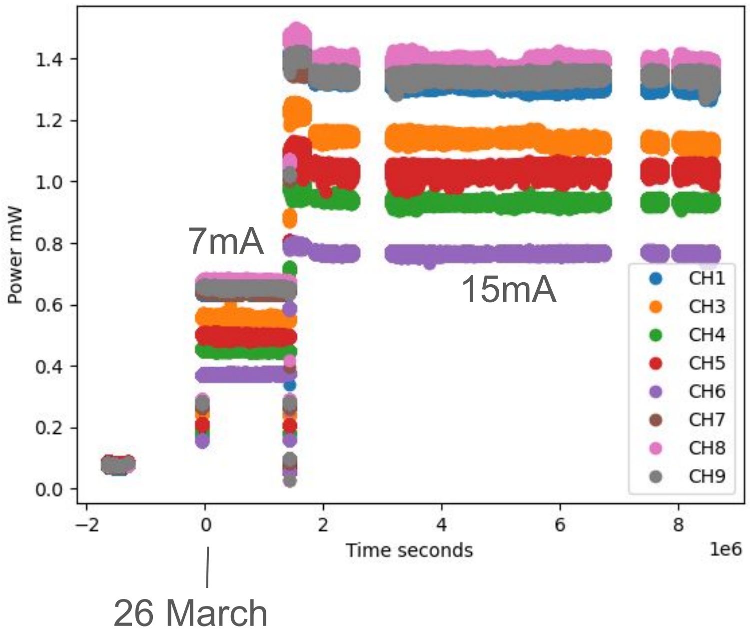
CAEN v1720 ADC (8 channels)

Warm electronics board for power and signal distribution to the cold boards

Noble Liquid Test Facility (NLTF) - PAB, Fermilab

- Two fixed bias current runs
  - 7mA (1 months)
  - 15 mA (~3 months)
- Optical Power measured per second (48 - channel power meter)
- Power levels show small movements
  - Temperature effect (internal temperature measured at Power Meter)
  - Levels move up and down (<10%)
  - Main power outages
- **No laser failures**
- Lost 12 channels - fiber broken (flange over-tightened)
- Two analyses performed on data to characterise any long-term changes in power, both assuming exponential time-dependence
  - Down-sampled raw data
  - Day-averaged power with corrections for ambient temperature movement
- **No sign of aging**
  - No dependence on current
  - No consistent decreases

Raw data from power meter

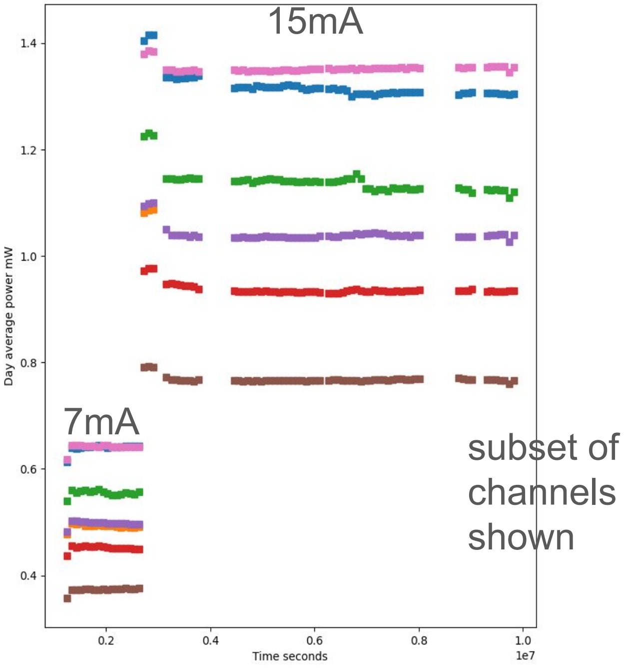


subset of channels shown

Longevity Studies

Day-averaged power

- RUN 1 at 7mA (15 days) RUN 2 at 15mA (51 days)
- Fitting to each channel (exponential model, linear correction dependent on power-meter temperature)
- Estimate lower limits to time-constant
- Movement on average power not consistent with laser aging
    - Lower limits on time-constant from RUN2 longer than RUN 1 (because run is longer)
    - Any downward trends seen in RUN1 not observed in RUN2

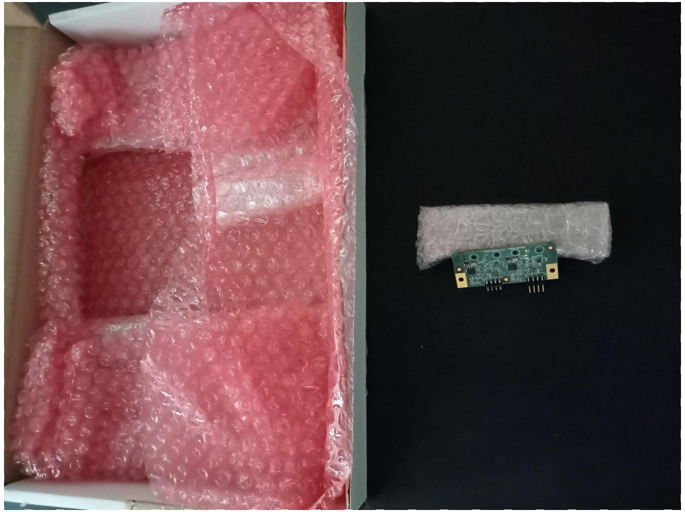


Pulsing

- All channels pulsed from 23 July - 20 August
- 8 channels, Koheron optical receiver and CAEN v1720 digitizer, stored waveforms
- Laser bias current low (giving 1uW optical power)
- Laser was pulsed
    - Frequency 1kHz
    - Pulse duration 1us
    - Pulse amplitude (from 1uW to koheron saturation 0.6mW)
- **All 8 lasers working after 2.4 10^9 pulses**

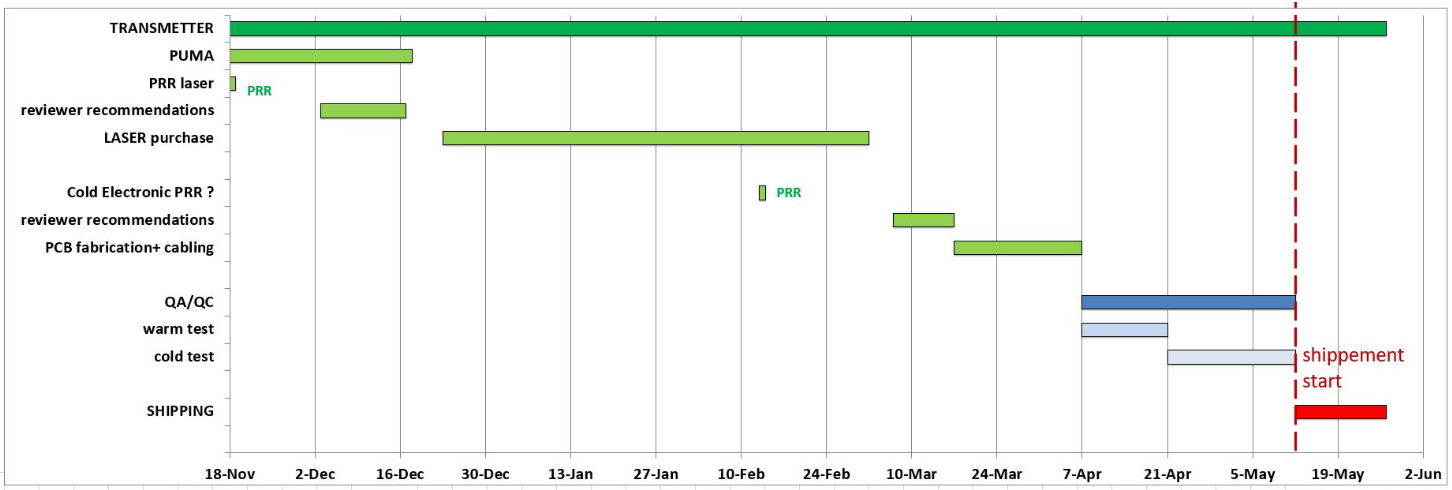
Procurement/Shipping/Storage Plan

- Component PRR for laser needed for spending schedule (2024)
- PUMA publication (similar to Request For Quotation)
  - Requirements document
  - 1 month from publication
- Lasermate quotation in reply to PUMA
- Delivery 10 weeks
- Lasers packaged, arrive with Lasermate QC documentation
- Cold Electronics PRR planned for February 2025
- Lasers sent (in supplier packaging) to cabling company (Ouestronic or Synapse) for cabling to PCBs
- Transmitter daughterboard PCBs return
- Testing procedure
- Repackaged in supplier packaging
- Stocked in anti-humidity cupboard at APC
- Accepted boards sent to CE assembly site UCSB (US) - 3 shipments
- 25%, 25%, 50% [adjust according to storage capacity at UCSB]



Schedule

TASK	Beg.	End	Duration (days)	
TRANSMETTER	1-Nov	27-May	207	
PUMA	*18-Nov*	*18-Dec*	*30*	
PRR laser	*18-Nov*	*19-Nov*	*1*	
reviewer recommendations	*3-Dec*	*17-Dec*	*14*	
LASER purchase	*23-Dec*	*3-Mar*	*70*	~10w
Cold Electronic PRR ?	*13-Feb*	*14-Feb*	*1*	
reviewer recommendations	*7-Mar*	*17-Mar*	*10*	
PCB fabrication+ cabling	*17-Mar*	*7-Apr*	*21*	30 working days
QA/QC	7-Apr	12-May	35	
warm test	7-Apr	*21-Apr*	*14*	
cold test	*21-Apr*	*12-May*	*21*	
SHIPPING	*12-May*	*27-May*	*15*	



QC plan

- QC approach
    - Vendor provides parts passing our requirements
    - We do not perform QC on isolated laser diodes
    - Our QC is performed on assembled cards
    - We have resources to purchase additional laser diodes to replace any post-vendor loss beyond spares quantity
- Vendor-supplied QC
    - Lasers tested at room temperature
        - Threshold current mA
        - Forward V (Vf)
        - Slope Efficiency S.E (W/A) - gradient
        - Pf - power at Ith + 20mA
- Lasers sent to cabling company with SOF PCB
    - No handling of lasers
    - Lasermate packaging
- SOF card testing program
    - Visual inspection
    - Room temperature
    - Deep liquid argon
- SOF-card tracking
    - Each SOF-card has serial number
    - Record S/N of lasers (ch1,ch2)
    - Serial numbers, and QC data/parameters stored DUNE database (contacted Gustavo do Amaral Valdiviesso, Mike Eads)

Model No. T13F-RFX-CR2G-F25S Date: 5/10/24

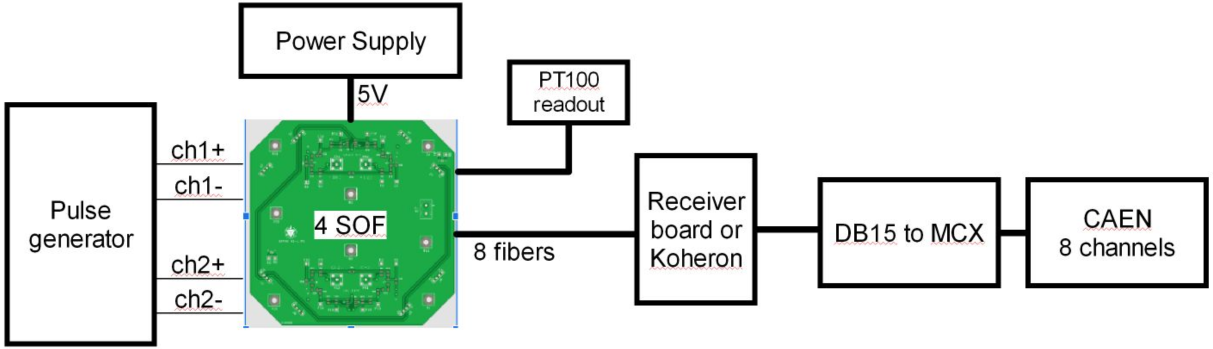
Serial number and test data [CW @ Tc=+25 ℃ , unless otherwise noted]

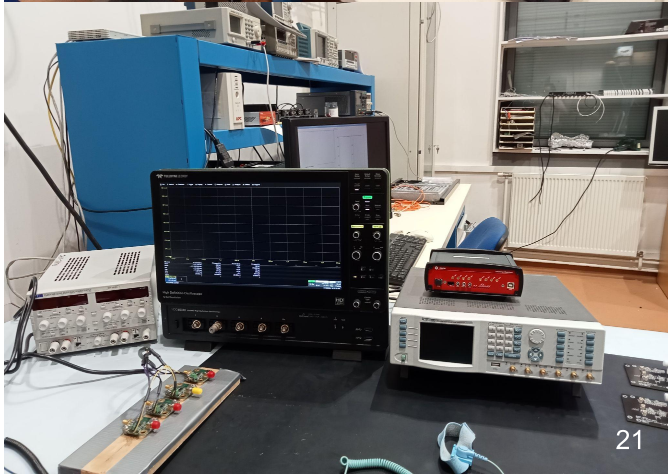
Condition : Pf=Ith+20mA

SPEC. / S/N	Ith (mA)	Vf (V)	Pf (uW)	Im (uA)	S.E(W/A)
	<15mA	<1.6V		>100uA	
240503001	9.68	1.23	161	380	0.008
240503002	10.36	1.25	175	324	0.009
240503003	10.26	1.24	175	317	0.009
240503004	10.11	1.23	173	358	0.009
240503005	10.43	1.24	182	326	0.009
240503006	10.48	1.25	178	328	0.009
240503007	10.40	1.25	194	327	0.010
240503008	10.37	1.24	199	436	0.010
240503009	10.46	1.25	176	268	0.009
240503010	10.53	1.25	175	322	0.009
240503011	10.32	1.23	192	317	0.010
240503012	9.52	1.22	174	363	0.009
240503013	10.52	1.24	166	330	0.008
240503014	10.59	1.25	169	327	0.008
240503015	10.41	1.25	166	316	0.008
240503016	10.46	1.25	175	322	0.009
240503017	10.23	1.25	187	319	0.009
240503018	10.35	1.24	180	300	0.009
240503019	10.68	1.24	187	268	0.009
240503020	10.04	1.23	170	379	0.008
240503021	10.51	1.25	164	319	0.008
240503022	10.65	1.24	178	317	0.009
240503023	9.78	1.23	167	380	0.008
240503024	10.54	1.24	173	327	0.008
240503025	9.89	1.23	178	349	0.009
240503026	10.51	1.25	178	325	0.009
240503027	10.65	1.24	174	397	0.009
240503028	10.38	1.24	186	314	0.009
240503029	10.84	1.24	174	416	0.009
240503030	10.75	1.24	181	323	0.009

SOF transmitter PCB testing

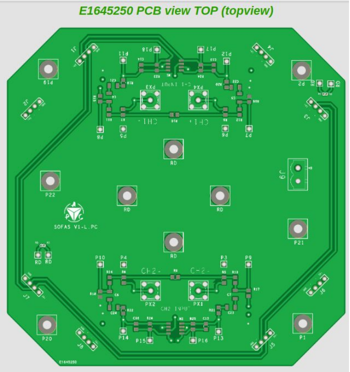
- Preparing automated test system for both warm and cold testing
- Test 4 SOF cards (8 channels) simultaneously with test motherboard
- Computer-controlled pulse generator (differential output), 8-channel CAEN digitiser (records waveforms)
- Waveforms analysed on the fly
- Parameters plotted for shifter (cf. acceptable range) and stored [DUNE database]
  - Laser offset (baseline) - optical power at fixed current (3mA)
  - Laser response with pulses (pulse amplitude in vs out) - Linearity, gradient, current threshold
  - Sinusoidal inputs - frequency response
- Estimate 15 (30) mins per 4 cards warm (cold)

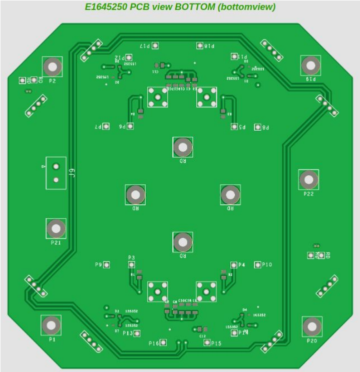


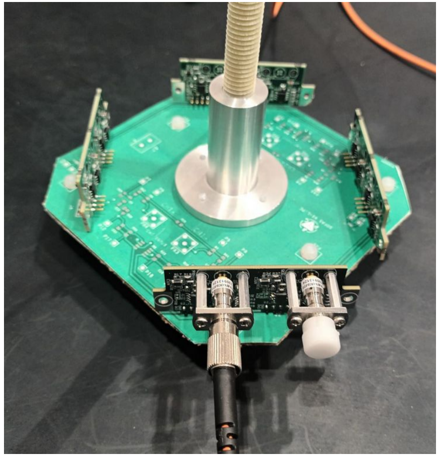


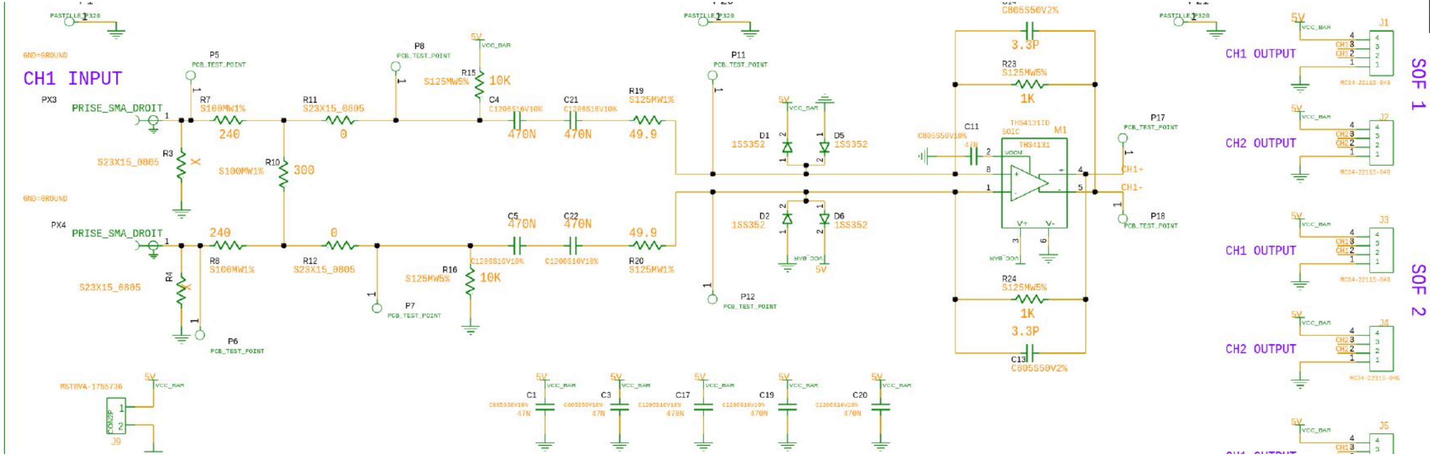
SOF transmitter PCB testing

- Test motherboard (similar electronics to DCEM)
  - Holds 4 transmitter cards
- Will be used for warm and cold tests
- Cold tests
  - Central post for immersion/retrieval in LAr
  - Drying station in development
  - Mock up ongoing









SOF-transmitter PCB testing

- Shift team comprises 1 expert (5 experts total) and 1 non-expert (APC DUNE member)
- Test procedure in preparation
- Mock-ups soon (test motherboard ready ~20 Nov)

Warm test procedure

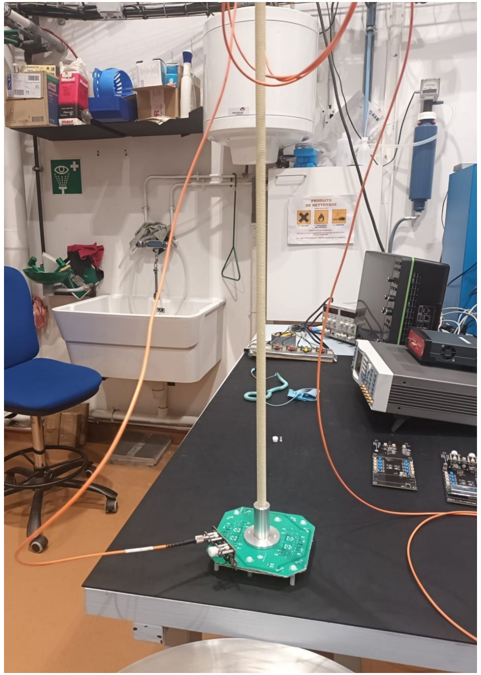
- Unwrap 4 SOF cards
- Visual inspection of 4 cards
- Clean fiber tips and connect to lasers
- Mount 4 cards in motherboard
- Run test program
- Are all measured parameters in acceptance range ?
- Dismount cards and re-package. Place in acceptance / non-compliance box

Expertise station equipped to check cards with issues

- Oscilloscope, anti-static mats and wristbands, receiver, camera etc

SOF-transmitter PCB testing

- Shift team comprises 1 expert (5 experts total) and 1 non-expert (APC DUNE member)
- Test procedure in preparation
- Cold mock-up test December/January



Cold test procedure

- Unwrap 4 SOF cards
- Clean fiber tips and connect to lasers
- Mount 4 cards in motherboard 1
- Immerse motherboard 1 in cryostat
- Prepare motherboard 2
- Run test program [immersed for at least 10 mins]
- Are all measured parameters in acceptance range ?
- Retrieve motherboard 1 and place in dryer
- Immerse motherboard 2 in cryostat
- Unplug receiver 1 from digitiser
- Plug receiver 2 into digitiser
- Dismount cards from motherboard 1 and re-package. Place in acceptance / non-compliance box
- ….

Expertise station equipped to check non-compliance cards

- Oscilloscope, anti-static mats and wristbands, receiver, cameras etc

Safety

QC testing at APC reviewed by APC laser safety officer: Matthieu Laporte

Decision letter included in documentation

- Laser class 1
  - IR laser (invisible), low power 2 mW
  - Laser is housed in FC receptacle for optical fiber connection, focus point is within housing
  - Laser is operated when connected to optical fibers
- Full-system (DCEM + SOF etc) safety plan to be addressed in cold-electronics PRR (February)

Summary of answers to charge questions

1. Has the consortium responded appropriately to the relevant recommendations from past design reviews and are they closed?
2. Are there any further relevant reviewer comments and recommendations based on design changes implemented since the FDR?
3. Has the current design been validated sufficiently to give confidence that the components to be procured are the correct ones?
4. Is there a credible plan in place for how the components will be procured? Are the required quantities including spares well understood?
5. Have the appropriate QA/QC requirements been defined to flow down in the procurement documents to the supplier?
6. Is there a credible plan for how the components will be shipped, handled and stored upon receipt?
7. Is an effective QC plan for acceptance testing in place in order to ensure the parts received meet specifications?

Q1,2: Summary of answers to PDR and FDR recommendations

R4. The SNR should be measured for several additional cathode and membrane modules, assembled with preproduction electronics.

[initial response] The Signal to Noise Ratio (SNR) will be measured for Module-1 test modules at CERN (including preliminary test in dunker) at the planned dedicated test run in fall (prior to the production readiness review). CERN test-stand and cold box measurements

R6. Perform integrated tests of long-term performance stability including all aspects of the CE design, along with extrapolations to the full channel count of FD2 for the anticipated 20+ year lifetime

A document summarizing the full long-lifetime/stability test plan was presented as part of the FDR documentation (EDMS 2887413). This document will be updated throughout the period leading up to the PRRs in spring 2024. TallBo longevity measurements for laser

R7. Establish an Engineering Specification of the SoF system covering the cold and warm portions as well as the optical fiber so that each portion may be designed and tested separately while still ensuring the final functionality of the full installed system.

An engineering specification document for the SoF readout system is under development,;can be found in EDMS-2906182. This document includes both high-level system specifications and component level SiPM mounting PCBs, cold electronics driver boards (DECM) etc. This document will be updated for the PRR.

laser requirements:

- Operates in liquid argon (defocused, perforated)
- frequency response greater than our signal (>20 MHz)
- threshold current in LAr < 3mA
- optical output (0 - 1.5 mW optical power for currents from 2 - 30 mA)

Q1,2: Summary of answers to PDR and FDR recommendations

R8. Demonstrate the operating margins of the SoF system to ensure that operational adjustment of the parameters is not required.

Following discussion with the Review Committee, this recommendation is understood to request engineering validation of the performance safety margins for the SoF readout system. this will be included in the high-level specifications section of the engineering specification document (See recommendation 7) For full CE PRR.

R11. Plan to test SoF & PoF systems after installation and connection at each DCEM using optical power levels below the eye-safe limit, before silicone potting.

Cold tests of modules will be made at CSU prior to installation. A warm test will be made at SURF during installation on cathode, before potting.

R16. Hold a workshop as soon as possible with relevant experts to define and validate the lifetime qualification studies and further develop the documentation with the status of the evaluation of the lifetime of every individual opto/electronic component in the system. Embark on the reliability and ageing tests as rapidly as possible to provide an initial assessment ahead of upcoming reviews.

48 laser diodes underwent an aging test (TallBo longevity tests).

R17. Plan for a long-term system slice-test, starting as soon as possible, beginning with final prototype components, with replacement to final production grade components when available. Leave these tests running until final installation of the detector at SURF to continue to gain experience.

The lasers underwent an independent aging test (TallBo longevity tests). ProtoDUNE-VD will test full system long-term.

Q3: Has the current design been validated sufficiently to give confidence that the components to be procured are the correct ones?

A large number of laser diodes have been purchased, characterized and used in SOF transmitters - Slide 9

SOF performance at cold box, CERN test stand	Slides 7-10
Laser diode response characterization	Slides 11 -12
TallBo longevity testing of 48 laser diodes	Slides 13-17

Q4: Is there a credible plan in place for how the components will be procured? Are the required quantities including spares well understood?

Procurement procedure described in Slide 18

Slide 12 gives an example of laser diode (channel) selection. SOF cards with 1 channel rejected, will have laser replaced. Work done in private sector/in-house depending on quantity. Then card will be re-tested (warm and cold). These SOF cards (~10%) will be used for spares, test-benches etc.

Lead time on the laser diodes is only 10 weeks so more lasers can be purchased if required.

Q5: Have the appropriate QA/QC requirements been defined to flow down in the procurement documents to the supplier?

We understand the information the vendor will supply with the laser diodes. These quantities describe the laser response at room temperature. We require that lasers are selected on these values (which is detailed in PUMA):

Threshold Current, Ith, in (mA) < 15mA
Forward Voltage, Vf, in (V) < 1.6V
Power, Pf, in (uW) (measured at diode current = Ith + 20 mA) > 100uW
Slope Efficiency (W/A) > 0.007

Q6: Is there a credible plan for how the components will be shipped,handled and stored upon receipt?

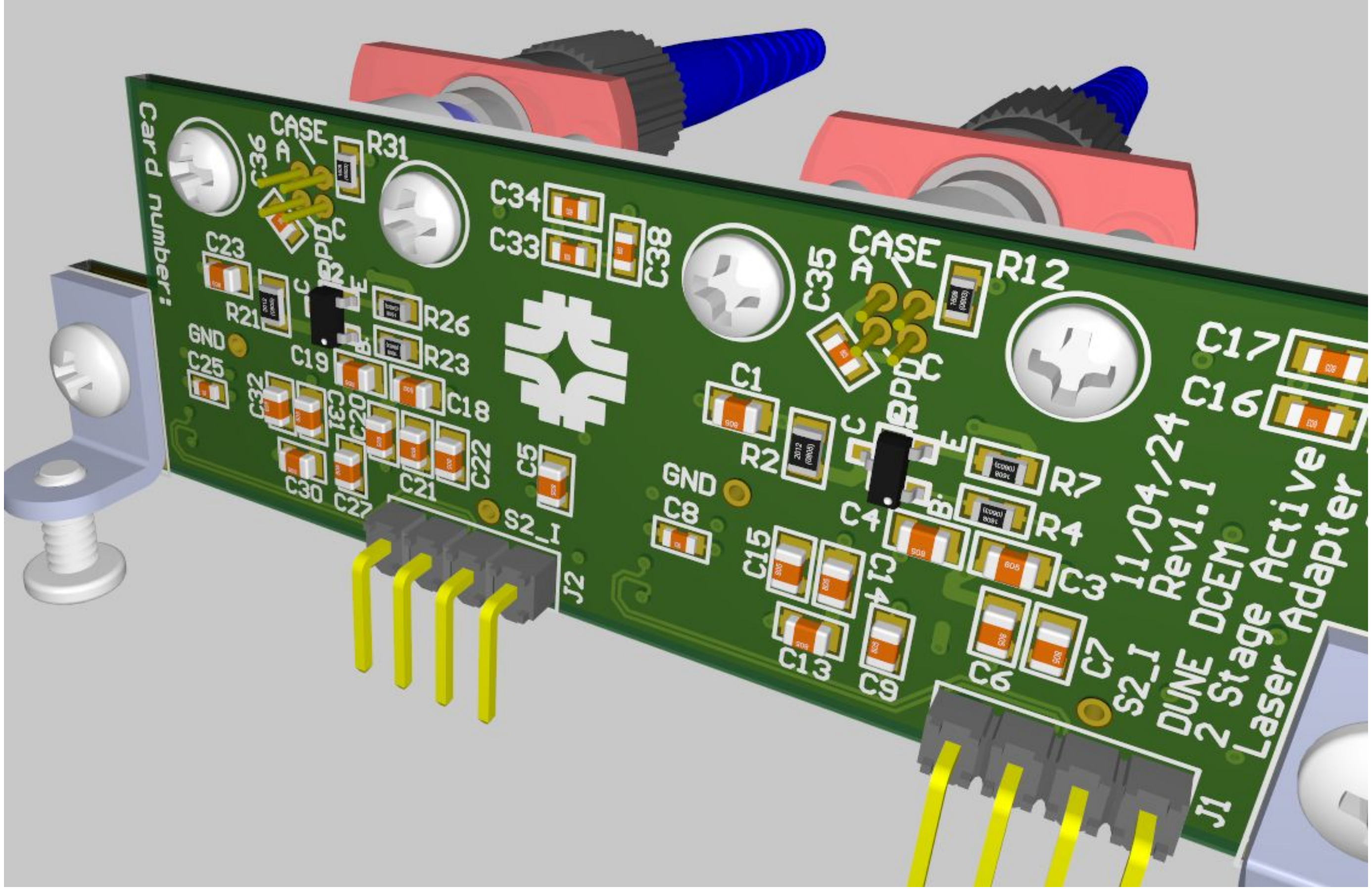
Procurement/Shipping/Storage summarised on Slide 18

Q7: Is there an effective QC plan for acceptance testing in place in order to ensure the parts received meet specifications?

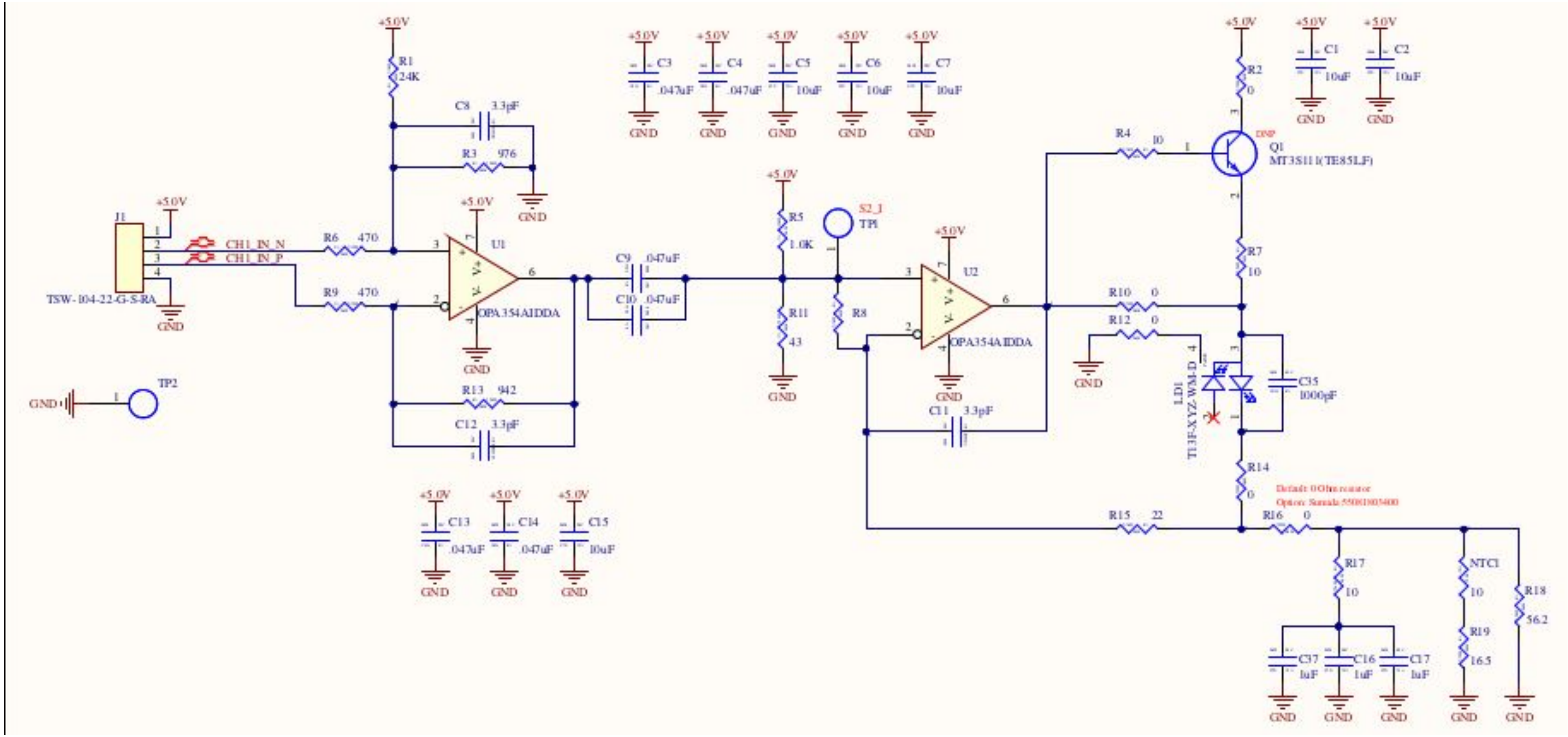
QC plan given in Slides 20 - 24

BACKUP

Laser Adapter 3D view



Laser Adapter Schematic



Version (SiGe/CMOS) controlled by BOM

DCEM Schematic - signal path